

Understanding and predicting the Indian summer monsoon

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This is a brief response to Sunita Narain's thought-provoking piece on the role of monsoon in our lives¹. As scientists actively involved in understanding the Indian monsoon and its prediction, we have attempted to elucidate what we know about this intriguing phenomenon, which is a tantalizing mixture of order and chaos, the problems of predicting it and our expectation of the progress that could be achieved in the near future. We have also touched upon how we could adapt to the variability of the monsoon and thereby 'celebrate our enjoyment with this rain creature, and deepen our engagement with the monsoon'.

How much do we know about the monsoon?

The distinguishing attribute of the monsoon is the large variation of the winds with season (which was the basis of the original definition of the monsoon by Arab sailors) and of the rain, which is our primary concern. Most of the rainfall over the Indian region as a whole occurs during June to September, which is known as the summer monsoon season. What is referred to as the monsoon in common parlance is the Indian summer monsoon rainfall and prediction of the seasonal mean monsoon rainfall is perceived to be the most important issue.

We know a great deal about the nature of variation of the monsoon from year to year as well as on shorter timescales such as the variation between wet and dry spells within the monsoon season, from analysis of the rich dataset extending over 100 years at many stations in the country. However, it is necessary to understand the physics of the monsoon and the mechanisms underlying its variability for developing models which can give reliable predictions. (A popular account of what is known about the monsoon and its variability is available in a series of articles on the Indian monsoon in *Resonance*, 2006–2008.)

We have been taught in schools that the temperature gradient between the heated subcontinent and the surrounding seas leads to the monsoon. This was the first hypothesis about the cause of the

monsoon, proposed by Halley more than 300 years ago. Our perceptions about the monsoon changed dramatically with the advent of meteorological satellites in the mid-sixties, which made it possible to literally see the intense cloud systems over the tropical oceans and land. Around the same time, the physics of tropical cloud systems of scales of hundreds of kilometres (such as in hurricanes or planetary scale rain bands) comprising thousands of individual clouds was unravelled. Over the last three decades, the basic system responsible for the monsoon has been elucidated and major advance has been made in our understanding of the mechanisms leading to its variability on different timescales². Studies in India have contributed substantially to the present understanding of the vagaries of the monsoon.

We now know that the system responsible for monsoon rainfall is not a gigantic land-sea breeze as suggested by Halley and several others, but a planetary scale system, which is associated with large-scale rainfall over all the warm tropical oceans and is seen in satellite imagery as an east-west band of deep clouds girdling the earth. This planetary scale system moves from the equatorial Indian Ocean onto our subcontinent during the advance phase of the monsoon in June, fluctuates primarily over the monsoon zone (region north of the peninsula) in July and August, and starts retreating southward from there in September. Thus we owe our monsoon to the annual visit of this planetary scale tropical rain band during the summer monsoon season and not due to just a local land-sea breeze. This has important implications for the variability of the monsoon. Although our primary concern is the monsoon rainfall on the landmass, we can ill-afford to ignore the events over the oceans surrounding the subcontinent. This is because most of the cloud systems which give us this rain are born over these warm oceans. Hence, the variation of the monsoon rainfall is linked to the variation of the cloud systems over the equatorial Indian Ocean, Arabian Sea and Bay of Bengal. On active monsoon days, the associated cloud band often stretches eastward from over the Indian region to

over the tropical Pacific Ocean. Not surprisingly, the major events over the Pacific, such as El Niño, have an impact on the monsoon and are in turn influenced by the monsoon^{3,4}.

Why do we need to predict the monsoon?

It is important to note that the year-to-year variation of rainfall averaged over the Indian region during the summer monsoon is characterized by a standard deviation, which is only about 10% of the long-time average rainfall of about 85 cm. The monsoon is clearly a rather reliable facet of the tropical atmosphere which invariably arrives year after year and gives us life-sustaining rainfall. Yet, the impact of this variation on agricultural production is high because 60% of the area is still not irrigated. Also, despite the rapid development over the last five decades leading to marked decrease in the contribution of agriculture to the GDP, the impact of droughts (seasons with deficit in the Indian summer monsoon rainfall over 10%) has remained 2–5% of the GDP throughout this period⁵. Thus of all the important meteorological events, it is the summer monsoon rainfall which has a long-lasting impact over a large spatial scale. Not surprisingly, the prediction of rainfall in the forthcoming season monsoon is awaited with baited breath, year after year.

Predicting rainfall over our region: problems and prospects

In the tropics, the most important meteorological variable is the rainfall. However, all the systems that give rain, i.e. the individual clouds, lows, depressions, hurricanes as well as the large-scale cloud bands, are end-products of atmospheric instabilities. Thus the prediction of rainfall in the tropics is inherently more difficult than, for example, that of eclipses which arise from stable orbits.

Meteorological predictions are made on different timescales. In the short range of a few days ahead, the interest is in where it will rain and whether there

will be very heavy rain (more than 20 cm in a day) at any one place. Heavy rain events are associated with deep clouds. Prediction of the growth and movement of cloud systems comprising deep cumulus clouds involves prediction of the growth of unstable modes for which accurate initial data are required. Satellites have made it possible to generate data on location and intensities of existing cloud systems, which can be assimilated as initial conditions for the complex numerical models of the atmosphere⁶. In the past few years the accuracy of prediction of rainfall, one to two days in advance, has been shown to be high when satellite data have been assimilated to specify initial conditions accurately. Thus it has been shown that the intense rainfall event which gave over 90 cm of rain over Mumbai on 26 July 2005 could have been predicted, if all the high-resolution satellite and radar data had been incorporated as the initial conditions of the existing models. Efforts to thus utilize all the satellite data for predictions are underway and we expect a further improvement in the short-range operational forecasts in the future. Since the system is chaotic, there is a sharp decline in the accuracy of rainfall prediction beyond two days because of the rapid growth of small-scale errors.

The long-range prediction of interest is the total rainfall in a season such as the summer monsoon over the country as a whole or some parts such as northwest India. The main determinant of seasonal atmospheric predictability is the slowly varying boundary conditions at the earth's surface. In particular, an important component of the variability of the tropical atmosphere arises from the variation of the sea surface temperature (SST). Forcing by these slowly varying boundary conditions makes it possible to predict rainfall, provided only averages over large spatial and temporal scales are considered. Thus while it will never be possible to predict the summer monsoon rainfall several months in advance at a single station (because of the limit of predictability of the chaotic system), it may be possible to generate reliable predictions for rainfall over the Indian region as a whole, using atmospheric models forced by predicted SST or models of the coupled ocean-atmosphere system. The last decade has witnessed enormous progress in the skill of such predictions for the other important tropi-

cal phenomenon, the El Nino over the Pacific⁷⁻⁹.

Prediction of the Indian summer monsoon rainfall has proved to be one of the most challenging problems in the field¹⁰. This is reflected in the failure of the complex models of the coupled atmosphere-ocean system at different international centres in predicting the severe drought of 2009. The skill of simulation of the mean Indian summer monsoon rainfall and its year-to-year variation by atmospheric models is rather low even when the SST is specified from observations. In the case of the African monsoon, models have been able to simulate not only the mean pattern but also the declining trend over the last four decades¹¹. The problems in simulating the mean Indian monsoon can be attributed to a special feature of the Indian longitudes (which is absent, for example, in the African monsoon). There are two dynamically favourable locations for the planetary scale rain band: one over the heated subcontinent (associated with our monsoon) and another over the warm equatorial Indian Ocean (where it resides before the onset of the monsoon). Thus one possible solution of the governing equations implies occurrence of the rain band only over the equatorial Indian Ocean, with most of the Indian region becoming an extension of the Thar Desert. The other solution is characterized by the rainbelt only over the monsoon zone. Models tend to get locked into one of the possible equilibrium states, whereas in nature the rain band fluctuates between the two states throughout the monsoon season. The onset phase of the monsoon involves northward movement of the oceanic band onto the monsoon zone. Even in July and August, the oceanic band appears intermittently and propagates northward onto the monsoon zone. In fact, the oceanic band is a life-line of the monsoon, since such northward propagations contribute substantially to the maintenance of the rain band over the monsoon zone. However, the oceanic band does not always play a positive role in the monsoon; when it is hyperactive it can suppress rainfall over the Indian region (as it happened in June 2009 when the all-India rainfall was close to half its average¹²). Simulation of this complex behaviour was a major hurdle in realistic simulation of the mean Indian monsoon rainfall. Now the mean rainfall is reasonably well simulated by several mod-

els, but simulation/prediction of the year-to-year variation is still a challenge.

At present statistical methods predict seasonal mean rainfall somewhat better than methods based on dynamical equations. For example, six out of the seven statistical models in the country predicted that the monsoon rainfall in 2009 would be below average (but the magnitude of the deficit was highly underestimated). Clearly, improvement in the skill of prediction of the year-to-year variation of the monsoon with dynamical models is a must. It is well known that this variation is linked to the major variation over the Pacific, viz. El Nino and the Southern Oscillation and most of the models are able to capture this link¹³. Recent studies have elucidated another important link with clouding over equatorial Indian Ocean¹⁴, which is well simulated in some cases by one of the state-of-the-art coupled models¹⁵. The dynamical models can be expected to improve further as they use finer spatial grid. This improvement is contingent upon using more realistic cloud models. Our understanding of the vertical structure of the clouds has improved recently on account of the satellite data from the Tropical Rainfall Measurement Mission. This satellite carried for the first time, a radar in space and provided a comprehensive data base on the vertical structure of the clouds. With the launch of the Indo-French satellite, Megha-Tropique⁶ and assimilation of all the high-resolution satellite data, the short-range forecasts are bound to improve in the near future. With further research in the physics of the year-to-year variation of the monsoon and development of the models, we expect substantial improvement in the skill of prediction of the Indian summer monsoon rainfall within a decade.

It is important to note that instabilities of the system imply that there will always be uncertainties in atmospheric prediction beyond the limit of deterministic chaos. Hence predictions for rainfall for a season as a whole are given in terms of probabilities of rainfall in different ranges, such as drought, normal, above average rainfall, etc. The basic probabilities of occurrence of different categories come from the observed variation. For example, for the Indian summer monsoon rainfall, on the basis of historical data for the 20th century, we can say that the probability of droughts (deficit

of all-India monsoon rainfall larger than 10% of the average rainfall) is 18%. The prediction for a specific season would suggest how the probability distribution would change. Thus if the skill of the models was adequate, the prediction for 2009 would have been for a much higher probability of drought than the climatological probability of 18%. Our strategies for not just for surviving but thriving in the monsoonal region should, first and foremost, involve adaptation to the climate variability of the different regions. When reliable predictions become available then the strategies appropriate for the predicted probability distribution for the specific season should be adopted.

Adapting to monsoon variability

The large impact of the variability of the monsoon on agricultural production because of a large fraction of the cultivated area being rainfed, is well known. In fact, the productivity of rainfed regions has not increased significantly in the last five decades. The green revolution, which was based on high-yielding varieties that demanded adequate and timely application of inputs, not the least of which was water, bypassed the rainfed regions. In the approach adopted for rainfed regions, rainfall variability is generally viewed as an unavoidable calamity and strategies to minimize the impacts such as drought-prone varieties (which will not be suitable during most of the years) are promoted. No attempt appears to have been made to use the known rainfall variability as a resource rather than a threat. Yet we possess a wealth of data on rainfall variability across the country, which can be utilized to derive farming strategies that are

tailored to local rainfall variability. Mathematical models for growth and development of plants have been developed over the last two decades for several crops. These models realistically simulate how crops respond to varying rainfall at different stages. These crop models make it possible to choose appropriate strategies, such as identifying the optimum sowing dates for a given crop or opting for alternate cropping patterns so that we can reap benefits of good monsoon seasons while minimizing the adverse impacts of droughts. Thus, by combining the vast information we possess on monsoon variability with modern tools such as crop models, we can find ways to help the farming community achieve sustained increased production.

In addition, strategies for coping with calamities such as droughts have to be developed. Many may not know that such strategies existed before the colonial era. This is evident from a report by the British Governor of Bombay on the impact of the drought of 1876–1877 on a region in northern Karnataka. The Governor stated: 'Despite vast loss of the crops, the majority of the general population and almost the whole of the peasant proprietors sustained themselves without assistance from the state.' He added: 'How strong must have been the supporting power of the people, how large must have been the stores and stocks of food grains, how extensive their credit, how great their means of purchasing supplies from a distance and how resolute their spirit of self help.' Unfortunately these strategies and networks were destroyed in the colonial era. It is up to us to revive them in the modern context.

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